IV. — Recent Astronomical Progress.

The fact that the existence of our race depends upon an equilibrium among violent opposing forces, of the continuance of which science can give us no assurance, forms one of the most suggestive discoveries of recent times. That the conditions on which our civilization depends are themselves dependent on terrestrial temperature, and could not be maintained through any great and sudden change of that temperature, must have been obvious to thinking observers in all ages. That the temperature of the earth is dependent entirely on solar radiation, and might rise or fall to any extent through changes in that radiation, is a proposition which could not at any time have stood much in need of proof, and which all investigations into the subject of heat have helped to confirm. As a consequence of these propositions, it needs only a small change in the quantity of heat received from the sun to produce the most important changes in the means of our sustenance, or even to destroy them entirely. This subject has, however, never given rise to much consideration, because not only have the causes on which the sun's heat depends seemed inscrutable, but the possibility of any change in its amount has never been suggested by any natural occurrence. We count on the perpetual invariability of that which we see to remain constant from age to age with the same blind confidence which we repose in the stability of the earth itself. In the absence of any exact knowledge of the physical constitution of the sun, there is nothing unphilosophic in this confidence, since long endurance without change affords one of the best proofs of stability, so good, indeed, that unless we look much farther into the future than our interests commonly extend, it cannot be overturned by any knowledge of the sun which the present generation can hope to acquire. But the wide generalizations of modern astronomy lead to the conclusion that our confidence must have a limit, however wide that limit may be. We have every reason to believe that the physical constitution of the thousands of stars which stud our sky is the same with that of our sun, and we know that a number of them are subject to variations

of light so great that similar variations in our sun would be productive of the gravest consequence to the well-being of mankind. It is true that this number is but a small fraction of the entire number known; but, on the other hand, the period during which accurate estimates of stellar radiation have been made is so small that we cannot say how many stars may, in the course of a century, be found subject to slow and irregular variations. As a matter of fact, we know that estimates of the relative magnitudes of the stars made a century or two ago are in many cases strangely discordant with the present magnitudes; and while the general disposition of astronomers is to attribute these discordances to the fallibility of the older observers, the hypothesis of change cannot be entirely disproved.

The analogy of our sun to the fixed stars, and the possibility that it may, in some remote age, be subject to great changes, invests the question of its constitution with a peculiar interest. It is therefore not wonderful that the science of solar physics, (if one can regard it as a science), though entirely a growth of the last twenty years, we might almost say of the last ten years, occupies a prominent place among the subjects of astronomical research at the present time. The most important instrument of this research is, of necessity, the spectroscope. The immense distance at which the sun is situated renders every feature invisible with the telescope, unless it extends hundreds of miles both in breadth and height. The difficulty is aggravated by the circumstance that the sun's rays always produce undulations in the atmosphere, which prevent that object from being studied with high telescopic powers. But space produces no change in the composition of the light which passes through it, so that spectrum analysis can be applied with equal success to a flame in the hands of the experimenter, or to the most distant nebula revealed by the telescope. The instrument in question is the only one by which any definite idea of the constitution of a body can be formed by an examination of the light which emanates from the body. At the same time, it can hardly be denied that the seemingly marvellous performances of the spectroscope, especially its power of detecting chemical elements present in the heavenly bodies, have given rise to very exaggerated ideas of what it is really

capable of effecting. The enthusiasm with which it is sometimes regarded can hardly fail to be damped by the reflection that it can give us no definite information respecting the composition or nature of a solid or liquid body under any circumstances whatever. All such bodies, heated to redness, if not vaporized, give the same spectrum whether they are in the form of a large mass or masses, or whether they are divided up into the minutest particles, like smoke. If they shine by reflected light, the spectrum is that of the body from which the light emanated, and the spectroscope cannot even inform us whether the light has come directly from its first source, or whether it has undergone reflections during its course. Its "revelations" are entirely confined to bodies in the gaseous state. When we say that iron and magnesium are found in the sun, we mean only that the vapors of those bodies are found around the sun Even here, the problem is not always the simple one it was once supposed to be. The spectra of the same gas or vapor, at various temperatures and pressures, differ so widely that hardly any resemblance between them can be recognized.

In view of these facts it will not be surprising that we are still far from being able to say what the sun is, and what is the nature of the operations we see going on at its surface on so astonishing a scale. The observed facts are at the same time so numerous and so fragmentary, and the forces in operation so unlike any we see around us, that it is very difficult to make a summary of our present knowledge of solar physics. The difficulty is aggravated by the circumstance that if we attempt to go beyond the naked facts of observation into a region which can be properly called that of science, we find a conflict of opinion which reminds us more of the disputes of the old theological fathers than of the generalizations of modern science. A critical examination of these differences would perhaps show that investigators do not always bear in mind the fundamental principle on which any really scientific explanation of celestial physical phenomena must rest, namely, that such explanation must always accord with the properties of matter and the laws of force which we see around us. Possibly such an explanation may be out of the question, from

matter in the celestial spaces exhibiting itself under forms it can never be made to assume on the earth. If this possibility be admitted, we must either give up every attempt at explanation, or form some idea of the forms which it is possible for matter to assume when, on the one hand, exposed in the celestial spaces without the atmosphere which environs all objects on the surface of the earth, or, on the other hand, subjected to the violent forces we see in operation at the surface of the sun. We must therefore, at present, confine ourselves to a brief statement of what recent research has shown that the sun may be, rather than say confidently what it is.

All telescopic observers from the time of Galileo down have seen that the visible surface of the sun is a shining sphere, into the interior of which it is impossible for sight to penetrate. Indeed, we might say that this has been seen by all mankind in all ages, were it not for the possibility that the sun was a flat disk instead of a sphere, — a possibility which was first precluded by the telescopic discovery of the sun's rotation. And modern research has been able to tell us astonishingly little more about the constitution of this surface than that it is a shining sphere. At first the spectroscope was supposed to show that it was certainly not gaseous, because it gave a continuous spectrum; but this inference was greatly weakened by the discovery of Frankland that gases might give a continuous spectrum when subjected to pressure. For aught the telescope or spectroscope can tell us, it may be a nearly continuous solid crust surrounding the seething interior which is constantly bursting through it; it may be of the nature of an immense sheet of broken ice floating in a hot liquid; it may be a mass of clouds floating in a hot atmosphere; it may be a gas rendered luminous under the immense pressure of its higher portions; or it may be something which we have not yet surmised. It is not improbably a combination of all these things. Whatever it may be, it is in a state of constant change. Were it an unbroken and unchanging crust, it would soon radiate all its heat and leave us in utter darkness.

One of the most remarkable features of the photosphere, which may yet furnish the clew to the true theory of its con-

stitution, is the stability of its form and position, which is in such striking contrast to what is going on above and below it. However rapid the changes which may go on in it, it preserves its general level with such constancy that the most refined observations have never detected any certain deviation from perfect sphericity, except minute depressions in the position of the dark spots which are generally found on its surface.

Until the year 1868, nothing definite was known of what might be outside the solar photosphere. The only occasions on which anything at all could be perceived occurred during those rare moments when the bright body of the sun was entirely hidden by the moon, and then it was found that the dark body of the latter was surrounded by two quite distinct classes of objects: the one a brilliant corona irregular in outline, and rising to the height of the moon's semi-diameter; the other a series of irregular masses of rosy-colored flames, which, though brighter than the corona, were generally so small that they would hardly be noticed by the naked eye. It was also found, by a careful comparison of a great number of observations of total eclipses, that a thin, red, glowing envelope of some sort surrounded the whole sun, and was of the same apparent nature with the red flames; but of the nature of this envelope nothing could be inferred. The application of the spectroscope by Lockyer and Janssen, in 1868, to the study of the gases and vapors immediately surrounding the sun opened a new era in solar physics. It was found that the sun was completely surrounded by a glowing atmosphere of which hydrogen was the principal ingredient, and which generally rose to a height of two, three, or four thousand miles above the photosphere. This was the red envelope, traces of which had been seen near the beginning and end of total eclipses, and which, at Mr. Lockyer's suggestion, has been called the chromosphere. It was now found to present phenomena so amazing that few have ventured to present anything which they would claim to be a complete and satisfactory explanation of them. An atmosphere surrounding an attracting globe should, according to the accepted laws of gases, preserve its general level. Especially should it do so when subjected to a gravitating force so immense as that which reigns at the sur-

face of the sun. But, instead of this, we find it thrown up into masses and columns of every conceivable shape, which sometimes rise to the height of fifty thousand or even a hundred thousand miles. These constitute the rosy-colored flames or "protuberances" seen during total eclipses. When we can tell to what force their elevation is due, we shall have solved one of the great problems presented by the sun. One explanation attributes them to eruptions of gas from the interior of the sun, which burst through the photosphere with a velocity amounting to a hundred miles a second or more. Some of the protuberances present so much the appearance of being due to this cause, that they are called eruptive. It is obvious that every mass of gas thus thrown out must immediately fall again, unless sustained by some unknown force; a mass thrown up with a velocity of a hundred miles a second would fall again in twenty minutes. A truly eruptive protuberance would be simply a fountain of hydrogen. But, although many of the phenomena may be thus accounted for, such is not the case with all of them, because cloud-like masses are sometimes seen suspended at a great height for hours in succession, in seeming defiance of the law of gravitation. Possible electrical forces may have come into play, but this is only a surmise. All we can say at present is, that the force which raises and sustains the protuberances is still unknown, and that until it is known our knowledge of solar physics is in a very unsatisfactory state.

The corona present the same difficulty in an aggravated form. At every total eclipse of the sun we see that the latter is surrounded by an irregular layer of matter of some kind, extending out to a distance exceeding his semi-diameter. This corona is sometimes spoken of as a solar atmosphere, but several considerations make it morally certain that it cannot be properly considered such. An atmosphere, properly so called, consists of an envelope or layer of gas or vapor, sustained by its own elasticity. The elasticity, the temperature, and the force of gravity being known, the density of an atmosphere diminishes in ascending, according to a well-determined law. Making any reasonable hypothesis respecting the solar temperature, we shall find that the diminution of density of the

most elastic known gas would be scores of times more rapid than that of the actual corona. Moreover, we should expect the outline of an atmosphere to be round and uniform, whereas that of the corona is extremely irregular and more nearly square than round. The most conclusive proof is, however, afforded by the passage, during modern times, of two great comets directly through the corona, without any sensible effects being produced upon them. The first of these was the great comet of 1680, the second and most remarkable that of 1843. The latter, at the point of nearest approach to the sun, was less than one hundred thousand miles above its surface, and passed through at least three hundred thousand miles of corona with a velocity amounting, at its maximum, to three hundred and fifty miles per second. To judge the effect of an atmosphere of the rarest kind upon a body moving through it with this velocity, we have only to compare the comet with an ordinary shooting-star passing through our atmosphere. At the height of forty or fifty miles the latter becomes so rare as no longer to reflect the light of the sun. Yet, at the height of one hundred miles, its density is such as to burn or destroy in a few moments a meteor passing through it at the rate of twenty miles per second. The destructive effect of an atmosphere on such a body is proportional to the square of the velocity, and therefore hundreds of times greater in the case of the comet than in that of the meteor. Supposing the former to be a body of considerable volatility, it would have totally volatilized by an atmosphere far too rare to be visible; while if it were a solid body it must have lost a large part both of its mass and its velocity. But all the observations made on it do not show the slightest retardation, nor did its aspect give any indication of so destructive an influence as the passage through an atmosphere would have been.

We are, therefore, forced to the conclusion that the corona must be a cloud of minute particles of matter partially vaporized by the intense heat to which they are subjected. This is rendered highly probable by the observations of Professors Harkness and Young, made in Iowa, during the total eclipse of August, 1869, which have since been confirmed by other observers. A bright line was found in the green part of the

spectrum, which has never been certainly identified with any line given by any terrestrial substance. The most suggestive result of this discovery is, that the corona is not composed of a confused mixture of the elements present at the surface of the sun, but is, at least in great part, some simple and as yet undetermined substance; perhaps a substance which is not found at all at the surface of our planet. The chemical problem to determine what the substance is, is not more important than the mechanical one of finding what sustains it against the gravitating force of the sun. Perhaps the most plausible explanation is that which attributes it to an irregular crowd of meteors revolving around the sun in its immediate neighborhood, and, perhaps, continuous with the zodiacal light. But even this explanation is beset with difficulties which it would be tedious to enumerate; and the most logical course is to give up every attempt at explanation till we have more facts, and, in the mean time, frankly acknowledge that the forces seemingly at play outside the sun are a complete mystery to us.

Although we cannot explain to our satisfaction what is going on immediately around the sun, it is clear that certain natural operations are going on there on a scale of which we can form no conception. Non-scientific language would fail to describe them, for the reason that they transcend not only everything we see on the globe, but everything which the wildest flights of poetic fancy ever imagined. "Floods and whirlwinds of tempestuous fire," "lakes of fire and brimstone," are perhaps the poetical epithets most applicable to the phenomena in question. But nothing which can properly be called fire exists at the surface of the sun, for the simple reason that the temperature is so high as to render combustion impossible. The chemical combinations implied by this term can only take place at such temperatures as we have in our fires and furnaces; at higher temperatures substances combine and separate with equal facility. The impossibility in question is much like that of boiling water in a region where the temperature is so high that water exists only as a vapor. Neither "flood" nor "lake" nor "sea," gives any conception of a mass of fluid ten thousand times the whole surface of our earth, and

deeper than the Atlantic is broad. Neither "whirlwind," nor any other term expressing movements of air, gives any adequate conception of a mass of incandescent gas, which, should it roll down upon us from the north, would, in twenty seconds after it crossed the St. Lawrence, be in the Gulf of Mexico, carrying with it the whole surface of the continent in a mass, not simply of ruin, but of glowing vapor, in which the vapors arising from the dissociation of the materials composing the cities of Boston, New York, and Chicago would be mixed in a single undistinguishable mass.

Great as are these movements, they are, probably, only faint reflections of what is going on inside the sun; the masses of hydrogen belching through the photosphere being but the *hors du combat* from the war of atoms going on in the interior. According to the theory now best supported, — the only theory, in fact, which accounts for the supply of solar heat, the matter composing the interior of the sun is in a state of complete "dissociation"; that is, owing to the elevated temperature, each individual molecule of matter pursues its course without forming any permanent combination with any other molecules. For example, although both oxygen and hydrogen exist, they do not combine permanently to form water, because, in case of a combination of two molecules, they are instantly separated by the impacts of a thousand other molecules. To prevent the interior from solidifying, the temperature must be on the same scale with the pressure to which the interior is subjected from the weight of the outside. The latter is constantly cooling by radiation, and thus convective movements are established on the scale we have described.

One of the first requirements for the further advance of an understanding of solar physics is a more minute and systematic study of solar phenomena, both with the telescope and the spectroscope. Hitherto this study has been left almost entirely in the hands of individual investigators, whose work, notwithstanding the zeal with which it is prosecuted, has not always the continuity and completeness which are desirable. The attention of leading men, on both sides of the Atlantic, has, therefore, been directed to the subject of founding one or more observatories for the exclusive study of the sun. Ger-

many, however, is the only nation, so far as we are aware, which has taken active measures to attain this end; and a "Sonnenwart," to be fitted up with every appliance which the observer can desire, and to employ the ablest physicists of Germany, is now in course of erection at Potsdam. The subject of such an observatory has been much agitated in England, but public opinion has been so much divided upon the subject that no definite conclusion seems to have been reached. In France a physical observatory has been organized near Paris, but we are not aware whether solar physics will be its specialty.

Our own country offers an immense advantage for the working of such an establishment. Being constructed for the especial purpose of studying the sun, its location should be chosen with almost exclusive reference to the facility with which this end can be pursued. Now, at all the European capitals where these establishments have been projected, the meteorological conditions are extremely unfavorable. The atmosphere is the greatest foe with which the astronomer has to contend, even at night, when it is undisturbed by the heat of the sun. It is far worse in the daytime, when the effect of the sun's rays upon it is nearly always such as to render refined observations impossible. In Northern and Central Europe not only is the sun obscured by clouds more than half the time, but when it shines the light reflected from the vapors in the lower regions of the atmosphere interferes greatly with spectroscopic observation. An elevated situation, where the air is transparent and the sky generally clear, offers advantages so great that they could not be counterbalanced by any completeness of instrumental outfit. There can be no doubt that more than one such situation can be found in our Western territories; and that we thus enjoy a natural advantage for the study in question which would enable us to lead the world in its pursuit. Happily we have conclusive proof of the correctness of this claim. In 1871 the Coast Survey fitted out an expedition for the express purpose of learning, by actual trial, whether any great advantage would be gained by placing an observatory in an elevated situation. The point chosen was Sherman, the highest spot reached by the Pacific railway, and the spectroscopic work was placed in the hands of Professor

C. A. Young. Although during the few months that the expedition remained there was an excessive and most unexpected proportion of cloudy weather, yet, when clouds were absent, so clear was the air and so free from reflected sunlight, that Professor Young was enabled to more than double the number of lines known to exist in the spectrum of the chromosphere. So great are the advantages thus placed within our reach, that it would be, on our part, a wanton disregard of them to place such an observatory of the first class in any situation where they could not be enjoyed.

In the most essential of all requirements for a scientific establishment, the purely intellectual ones, we are probably as well supplied as any other country. That the work is of a kind to which the genius of our people is well suited is evinced by the number of them who have shown the highest talent in its performance. In contriving the instruments of observation, no one was superior to the lamented Winlock. Of the lines in the envelope of gas and vapors immediately surrounding the sun, the greater number have been seen by no observer except Young. Through the smoky atmosphere of Pittsburg, Langley has made telescopic studies of the sun's surface so far exceeding all preceding ones in minuteness and detail, that their results have been eagerly seized upon by the advocates of rival theories of the structure of the photosphere to sustain their several views. Langley and Mayer have made measurements of the heat emitted by different parts of the solar disk which can hardly fail to lead to important results. Less directly applica le to the subject of solar physics, but equally worthy of citation to sustain the general proposition now being maintained, are the labors of Rutherfurd and Draper in the applications of photography to astronomical research.

It is, perhaps, a difficulty in the way of realizing this project, that its first cost is so ridiculously small alongside the importance of the subject. The very fact that the object to be studied is that on which all life on our planet is dependent lends an importance to the work which is not diminished by the admitted fact that we cannot assure the speedy attainment of any purely utilitarian results. Ultimate results of the highest importance are almost sure to be reached, for, as the sun is the

source of life, it is in the changes of that luminary that our race may be expected first to read of its end. So far as we can see, the sun is the only book of fate which will ever be opened to us. Yet, the cost of building a solar observatory, and supplying it with every appliance necessary for observations of the sun, would hardly exceed that of the average city residence of a gentleman of wealth. The necessary endowment for the support of the observers would, of course, be greater, but would not exceed the sums constantly appropriated to objects of less importance.

Notwithstanding the present extremely unsatisfactory state of our knowledge of the sun's constitution, the question of the age and origin of the solar heat has led to some very interesting results, the knowledge of which has not been so widely disseminated as it deserves to be. The progress of this question is strikingly illustrative of the principle that the sentiments of wonder and mystery are inconsistent with either entire ignorance or complete knowledge, and belong entirely to the intermediate state of partial or imperfect knowledge. Before the discoveries of Rumford and Carnot it was not at all surprising that the sun should have radiated heat for thousands or millions of years, and no reason was known why it should not continue to radiate it at an undiminished rate for indefinite ages to come. When it was once found that heat could be produced only by the expenditure of a something, the supply of which was necessarily limited, and that that expenditure necessarily involved a progressive change in the body from which the heat was emitted, what formerly needed no explanation became a mystery. It was like the flow of an unbroken stream of water from a vessel which we could examine on all sides, and into which we could satisfy ourselves that no water was flowing. A very simple calculation showed that even if the sun had the greatest specific heat of any known substance, it would not contain an undiminished supply for the historic period, much less for the geological ages beyond. All the obvious explanations which could be cited were so completely untenable, that it is not worth while even to cite them. About fifteen years since it was suggested, we believe by Helmholtz, that the supply of solar heat could be kept up by

the slow contraction of the sun itself; and this is now not only the generally received explanation, but, so far as human judgment can be trusted, the only possible explanation not founded on an assumed subversion of well-established laws of nature. We see the sun radiating an unceasing flood of heat into the celestial spaces, and we see that he does not receive any but the minutest portion of this heat back again, because, if he did, our planet would intercept the same portion of the heat on its return which it intercepts on its passage out, and thus we should receive as much heat from the sky opposite the sun as from the sun itself. The meteoric theory, which attributed the maintenance of the solar heat to the import of meteoric matter on the sun's surface, was speedily found to be entirely untenable, because, if the necessary number of meteors were present in our system, the earth would encounter them in such quantities as speedily to raise its surface to a red heat. And, in general, we may say that, without imagining the most fantastic combinations of causes, it is impossible to frame a theory of the external maintenance of the solar heat which will not be subject to the *reductio ad absurdum* that the earth and planets are receiving a proportional supply, and are rapidly becoming too hot to be habitable.

So far as the maintenance of the solar heat, not only at present but for several millions of years past, is concerned, the contraction theory fulfils all the requirements of science. As the sun cools it must contract in volume, and the heat generated by this contraction, or, rather, by the fall of the parts of the sun on each other which the contraction involves, will almost entirely replace that which has been lost. Our present knowledge of the mechanical equivalent of heat, and of the quantity of heat radiated by the sun, enables us to determine what amount of contraction is necessary to keep up the supply. The result is that a diminution of the sun's diameter by two hundred feet a year will just suffice for this purpose. This contraction would not be detected by the most delicate measures we can make in a thousand years; there is therefore no result of observation to militate against it. But it would become sensible at last, and it follows from the theory that the sun was perceptibly larger a million years ago than now. Being also,

in consequence, less dense, a greater contraction would have been necessary to produce the present supply of heat, and the diminution of bulk was therefore more rapid. The most important consequence of the theory is that the total duration of the solar heat is necessarily limited, because the amount of heat generated by the falling together of the entire mass of the sun from infinite space is limited, and would only serve to keep up the present supply for about twenty millions of years. If the amount of heat radiated was greater in former ages than now, the time it has endured must have been less than this; if the radiation was less, the duration would be longer. Great changes in radiation are not consistent with the continuance of life on the globe, for an increase of but a fraction of the present amount would cause the entire ocean to boil, while a yet smaller diminution would permit water to exist only in the form of ice. That the radiation should remain constant under any considerable changes of the sun's density is improbable; it is therefore improbable that running water and animal life have existed on the earth many millions of years. And it is inconsistent with the laws of nature, as we now see them in operation, to suppose that they have existed on the earth twenty millions of years; because, on the only hypothesis science will now allow us to make respecting the source of the solar heat, the earth was, twenty millions of years ago, enveloped in the fiery atmosphere of the sun.

The question may be asked, whether it is not within the bounds of possibility that new laws of nature may be discovered which will show our system as we now see it to be completely self-sustaining, and thus extend back indefinitely the time during which the surface of the earth may have been in its present state, and the sun may have shone with his present brilliancy. We reply that it would be a rash application of philosophy to pronounce any phenomenon impossible; and since science views all phenomena as products of natural laws, it would be rash to deny the possibility of a natural law adequate to produce any required result. But, if we limit ourselves to what all investigations permit us to consider credible from a scientific point of view, then we may pronounce certain supposed phenomena incredible, and declare their occurrence to

border on the miraculous. For instance, that our telescopes may reveal to us intelligent beings moving at will through the celestial spaces, presents itself as an extraordinary idea to all, an incredible one to many. But, in the present state of science, we doubt whether it is any more extraordinary or incredible than the idea that the sun is receiving from any external source a supply of heat equal to that which he radiates. And, the phenomenon of the conservation of the solar heat without a supply from outside, and without a progressive change within, leading to a state in which the supply must cease, would be a yet more miraculous one than that just supposed. Of course, if observations showed that the sun possessed the power of thus producing a perennial supply of heat from nothing, we should have to accept it, and modify our ideas of certain natural laws, just as in the case of our seeing beings flying through the celestial spaces; but in the present state of our knowledge neither of these suppositions can be admitted into the category of scientific possibilities.

We have spoken of solar physics as exclusively referring to the constitution of our sun. To prevent any possible misapprehension, it should be said that the sun cannot be successfully investigated except in connection with the stars, of which he is one, so that a solar observatory could attain its end only by being devoted to the study of suns in general. Nor should this mark the limits of its field, for it is quite likely that the laws of the conservation of the solar heat will be ultimately learned from the study of the gaseous nebulæ. The case is illustrative of the general rule that the operations of nature are so closely interlaced, that it is impossible to learn one thoroughly without learning a great number of associated ones.

The branch of astronomy which, at the present time, is most nearly related to the immediate wants of life, is that which treats of the celestial motions, using the latter term in its widest sense. It is unfortunate that we have no term employed generally and exclusively to designate this special branch. The term "physical astronomy," formerly much employed, is now equally applicable to, and more suggestive of the examination of the physical properties exhibited by the heavenly

bodies, and more especially to the work of the spectroscope. "Theoretical astronomy" is a term somewhat too vague and inclusive; and "gravitational astronomy" somewhat too narrow, though it has the advantage of being precise and definite, including just so much of the subject as involves the determination of the celestial motions from the theory of gravitation. A fourth term, not infrequently used, is "astronomy of precision," but this includes a qualification which should at least be aimed at in every branch of the science. Without attempting to select the best name, the nature of the branch can be concisely defined by saying that it is that branch of astronomy which predicts the motions of the heavenly bodies by combining the theory of gravitation, the laws of motion, and exact observations of the relative positions of the bodies whose motions are to be determined. The reason why it is most immediately associated with the wants of life is, that upon it depends the measurement of time by years and days, and the determination of positions on the surface of the globe.

When it was found by Newton that the movements of the moon and planets could probably be determined with entire precision by the solution of the purely mathematical problem of the relative motion of a system of bodies submitted to their mutual attractions, no difficulty was found in reaching a complete solution for the case of two bodies; but when the celebrated "problem of three bodies" was attacked, a complete solution was found to be beyond the reach of the ablest mathematicians of the time, and the efforts of their successors have met with no better success. The fact is, that extraordinary as are some of the performances of the mathematician, such as predicting the changes of the planetary orbits through thousands of centuries from data derived from a few years' observation, our mathematical analysis is totally inadequate to the rigorous solution of any but the more simple problems presented by the investigation of the earth and the heavens. This will not appear surprising if we reflect that all mathematical operations are ultimately resolvable into the four primary operations of arithmetic, addition, subtraction, multiplication, and division, combined with the extraction of roots, and some simple geometrical forms, and consequently, that when a prob-

lem transcends solution by these operations, it is beyond the power of the mathematician. But although a strictly rigorous solution of the problems presented by the motion of the planets is not possible, the efforts of the successive generations of mathematicians since Newton have resulted in the invention of methods by which the motions of the planets under the influence of the attraction of the sun and of each other may be approximated to with any required degree of precision. By the application of these methods, combined with long and numerous observations, tables of the motions of the larger planets have been constructed, which represent their positions at all times with a precision which, from any other than an astronomical stand-point, is very great.

One of the most important and interesting questions suggested by these results is whether the actual motions of the planets accord perfectly with the theory of gravitation. This question is not quite settled either in the affirmative or negative, the difficulty in the way of the settlement being that observational astronomy is far ahead of theory. The labor of constructing a theory of the motion of any one planet from the law of gravitation, and of correcting the elements by comparison with all the observations extant, is so immense that it is undertaken only at long intervals. The latest tables of Saturn, for instance, are more than fifty years old. Again, the more modern tables are imperfect, from a want of exact knowledge respecting the masses of the planets. When, then, small discrepancies are found, it is not always possible to say whether they arise simply from an accumulation of small errors in the data on which the computations of the mathematician are founded, and errors in the computations themselves, or whether they indicate an actual deviation of the planet's motion from its normal course. At the present time, the earth is the only planet which is found to follow its tabular motions with such precision that no pronounced deviation can be detected. In most of the others, though deviations exist, they are so small that we may attribute them to the imperfections just described. Exceptions to this are, however, found in the case of Mercury and Saturn. Le Verrier found the perihelion of the former planet to be subject to a motion of 36″ a century, which could not be

accounted for by the attraction of the known planets; and on this deviation he founded his hypothesis of a group or ring of small planets between Mercury and the sun. The existence of such a group, adequate to produce this effect, seems hardly possible for two reasons. One is, that no trace of it has ever been seen, unless the matter giving rise to the zodiacal light be regarded as forming a mass sufficiently great to cause the observed deviation. Unless the supposed planets were so minute that it would take thousands of them to produce the required effect, they would frequently be seen to pass across the face of the Sun. But none of the astronomers who have so carefully and assiduously observed the sun during the past fifty years, have ever seen such a transit, the supposed observations of the phenomena being nearly all by observers otherwise unknown. As for the zodiacal light, it seems highly probable that there can be matter enough in it to make up a moderate-sized planet. The other reason is that such a group of bodies, even if we suppose the zodiacal light to constitute the group, would scatter itself near the plane of the ecliptic, and would, in consequence, produce a very sensible change in the position of Mercury's orbit. But no such change of position is indicated by the observations. We can, therefore, only say that in the case of this planet, the discrepancy between theory and observation has not been satisfactorily explained. In the case of Saturn it is quite likely that the discordance arises from errors in the theoretical computations, the theory being the most difficult of that of any large planet, and the results having never been subjected to sufficient verification.

Of all the heavenly bodies, the moon is the one which has given the mathematician and astronomer most trouble, from the days of Hipparchus until the present. The history of their efforts might suggest the idea that our satellite had always amused herself by eluding the efforts of mankind to predict her motions. Every complete theory of her motions has been found in error by the generation or the age immediately following its promulgator; and although the magnitude of the errors thus found has, on the whole, greatly diminished, the difficulty of accounting for them is still as great as ever. The deviations which now cause most trouble are apparently of long period;

that is, during a long period of years, perhaps half a century or more, the moon gradually moves ahead of her predicted place, and during other periods falls behind it again. These deviations were first detected by La Place, from the observations of the eighteenth century, and several ways of accounting for, and representing them, were suggested by him. But all his explanations have since been found inadequate in theory, and inconsistent with subsequent observations. The phenomenon remained entirely unexplained until it was found by Hansen that deviations of this kind in the moon's motion might be produced by the action of the larger planets on the moon, especially Venus, and, after long and tedious calculations, he announced the discovery of two such inequalities, the one having a period of two hundred and sixty-five years, the other of about two hundred and forty-three years. By adding these two inequalities to the tables, the motion of the moon from 1750 to 1850 was found to be represented with as much accuracy as the observations admitted of.

These inequalities have their origin in a sort of musical rhythm among the motions of the earth, the moon, and Venus. If from eighteen times the mean motion of Venus we subtract sixteen times the mean motion of the earth round the sun, the difference will be found nearly equal to the mean motion of the moon in anomaly. This relation gives rise to the first of Hansen's inequalities. Although the gravitation of Venus on the moon is nearly insensible, the result of this harmony of motion is that the attraction of the planet is felt, just as a musical string vibrates in response to a note in unison with it. We have here as good a realization of the "music of the spheres" as the hard unpoetic spirit of modern science could be expected to produce. The second inequality arises from a relation between the mean motions of the earth and Venus simply, namely, that thirteen times the period of revolution of Venus is nearly eight years, the same relation which leads to the return of a transit of Venus in the course of eight years.

The addition of these terms to the moon's longitude gave rise to much discussion, the result of which was to show that they failed to meet the requirements of the problem. Two distinct questions are involved in this discussion, one a purely

mathematical one, the other one of observation. The first is whether the resultant of the attraction of Venus on the moon, the earth, and the sun is certainly such as to give rise to the terms calculated by Hansen. The latter pronounced the computation of the terms in question to be the most difficult problem which presented itself in the theory of the moon's motion; and in calculations of such complexity, it is extremely difficult for any one mathematician to make sure that his results reach the required degree of accuracy. Hansen himself was never satisfied with his computation of the second term, and was finally forced to determine its value, not from the law of gravitation, but from observations. When the problem was attacked by others, it was found that while the first of Hansen's new terms was undoubtedly correct, the second was not, the deviation due to the fact that thirteen periods of Venus make nearly eight years, being found too small to be noticed in the observations. The second question, to be treated in a wholly different manner, was whether by the addition of these terms, the motion of the moon would agree with observation. Since, by the aid of two terms, Hansen satisfied the observations from 1750 to 1850, it is clear that when one of his terms was removed, the agreement would be destroyed. The result was, therefore, that the best mathematical theory was not in accord with observations. Still, Hansen's second inequality might exist, and be due to some other cause; and the greater the time during which it represented observations, the stronger the evidence in its favor. It therefore became important to compare Hansen's tables with observations before 1750, and after 1850. The few comparisons made with the imperfect observations before 1700 seem to show that they were then considerably in error. This result, owing to the imperfect character of the observations of those times, is hardly conclusive. It is, therefore, on recent observations that we must mainly depend for a settlement of the question. The tables in question were printed in 1857, and the places of the moon from them first appeared in the British Nautical Almanac for 1862. It was found that up to that period the agreement of the tables with observation was good. But, since that time, the moon has been falling behind the tables at

such a rate that her computed longitude is now ten seconds in error, — a quantity small in itself, but which would lead to an error of five miles in the terrestrial longitude of any point on the land or at sea determined from observations of the moon.

Such being the result of the latest investigations on the subject, it appears that the motions of the moon still elude the skill of the investigator. But the question is now taking another shape, and we have to inquire whether, after all, the seeming irregularities may not be in the rotation of our earth on its axis, and not in the moon at all. When we accuse a railway train of being behind time, we must inquire whether our clock is not too fast. In the present case the moon is the train, making its successive revolutions around the earth; and the latter is the clock marking the time for us by its revolution on its axis. The indications of this clock have hitherto been received with entire confidence, it being supposed that there was no possibility of any deviation of the rotation of the earth from perfect uniformity. But it is now conceded that such deviations are not impossible, and their detection, if they exist, must be considered as one of the most important astronomical problems of the present time, as well as one of the most difficult ones. What is wanted is an umpire between the earth and moon, — a means by which we can decide whether the moon is behind time or the earth is fast. A perfect clock, which would go for half a century without deviation, would settle the question, but this is mechanically impossible at present. The umpire must be some celestial body revolving fast enough to enable us to measure time by its revolutions. The one best suited for this purpose is Jupiter's first satellite, which makes a revolution around the planet in about forty-two hours, and is eclipsed in its shadow every revolution. Unfortunately, observations of these eclipses are so difficult that their uncertainty amounts to a considerable fraction of the discrepancy between the earth and moon; it is therefore only by a long and laborious course of them that a decision can be reached. It may, however, be said that the most recent observations decidedly favor the view that the error is in the rotation of the earth, and not in the motion of the moon. Should this be confirmed, we must remove our satellite from

the small and uncertain list of planets which do not move in perfect accord with the theory of gravitation.

By the successive improvements in mathematical methods which have been introduced in the course of the present century, especially by Hansen, a great increase of accuracy has been gained in the methods by which the motions of the planets are determined from the theory of gravitation. To make this improvement really fruitful, a corresponding improvement must be made in the accuracy of astronomical observations. Such an improvement has actually been realized in the course of the last thirty years, and may be illustrated by the large correction to the formerly supposed distance of the sun, which has been learned from recent investigations on that subject, and which lends much additional interest to the results which it is hoped to obtain from the recent transit of Venus.

It is well known to all who take an interest in astronomy, that the distance of the sun, deduced from the transits of Venus in 1761 and 1769, was a little over ninety-five millions of miles; and that this result was received with unquestioning confidence until quite lately. Had it been impossible to determine the distance in question in any other way than by transits of Venus, any improvement on this result would have been impossible until after the recurrence of the transit in 1874. In fact, however, several other methods are found applicable, which rival in accuracy the best observations of transits of Venus; and these methods all agree so well in indicating a diminution of the distance by some three millions of miles, that, for the last ten or fifteen years, there has been no doubt that the results of the old transits were affected with this enormous error. This discovery was confirmed when the subject of observing the transit of 1874 began to excite attention; it therefore became important to determine with some certainty the cause of the error, in order to avoid it in the observations now to be made. The fact seemed to be that observers were mistaken by amounts varying from half a minute to nearly a minute in observations, which it had been supposed could be made within one or two seconds, and in which the observers themselves supposed they had attained

nearly this degree of accuracy. It therefore became desirable to submit the older observations to a re-examination, with a view of throwing light on this subject.

This work was first undertaken by Powalky, a Berlin computer. He showed that if certain of the old observations were rejected entirely, and the result made to depend solely on the others, a value of the solar parallax would be reached agreeing well with those recently obtained. Unfortunately he did not show any conclusive reason for rejecting the observations which led to the erroneous result, which were, to all appearance, as reliable as many which were retained. He could not, therefore, be said to have satisfactorily answered the question.

The only other astronomer who has published a formal investigation of the subject is Mr. E. J. Stone, then first assistant at the Royal Observatory, Greenwich, and now Director of the Royal Observatory at the Cape of Good Hope. The well-earned astronomical reputation of Mr. Stone, together with the enthusiasm displayed by English writers on scientific subjects in making known the merits of any scientific work of their countrymen, have given a world-wide celebrity to his work, and rendered a critical description of it not uninteresting. To understand the questions raised in it, and the application of the principles involved to the subject of observing the transit of 1874, it is necessary to describe and explain certain optical appearances remarked by the observers of the transit of 1769. Let the reader imagine the planet Venus as a dark round disk entering upon the sun. As it passes over the sun's limb it makes a deeper and deeper rounded notch in the latter, until it is half upon the sun. Continuing its course, at the moment in which it enters wholly upon the sun, the two sharp cusps of the sun, which it serves to form, meet together behind it, forming a continuous thread of light, and the planet is wholly surrounded by sunlight. The moment when this occurs is that of internal contact of the limbs, and this was the moment which the observers were required to note with all possible precision. When the planet is about to leave the sun the same appearances take place in reverse order. As it approaches the edge of the sun the strip of sunlight between

the edge of the planet and that of the sun grows thinner and thinner; it is reduced to a thin thread, and then, when the planet actually reaches the edge it is broken off, and two separate horns, or cusps, are formed. This moment was also to be noted as that of second internal contact. It was believed that these moments could be noted without an error of more than one or two seconds, which would lead to the distance of the sun being determined to a small fraction of a million of miles.

But when the observers reached their stations and proceeded to note the phenomena, many of them were perplexed by an unexpected behavior of the planet, which prevented their making a satisfactory observation. When the planet had seemingly entered entirely upon the sun, the cusps of the latter did not close immediately up around the planet as had been expected, but the latter seemed to stretch out toward the sun's limb, and to be joined to it by what looked like a "black drop." When this drop finally broke, the planet had entered upon the sun by a quite sensible amount. Again, at egress, half a minute or so before the planet seemed to be going to reach the edge of the sun, this same black drop suddenly stretched itself across the interval, leaving the observer in doubt whether the contact had taken place or not. In this case there were two courses open; the observer might note, as the time of contact, that at which the black drop first appeared, or he might wait until he estimated that the round limb of the planet had reached the edge of the sun. This time, however, could not be estimated with any accuracy, because the black drop prevented the limb of the planet from being actually seen at the critical point. The cause of this troublesome phenomenon was first pointed out by Lalande, who showed it to be due to irradiation, or to the sun looking larger and the dark disk of Venus smaller than they actually were. This explanation has since been universally admitted, the only modification of it being the discovery that the large amount of irradiation necessary to produce this appearance was due to the imperfect quality of the telescopes of that time; and that with the better telescopes of the present time scarcely any appearance of the black drop is seen, unless the atmosphere is so undulating as to interfere with vision.

Mr. Stone's ingenious explanation of the error in the former results was founded upon the possibility that an observer might, at contact, note either of the two phases we have just described, namely, at ingress he might observe the moment at which the planet was, by estimation, wholly within the sun's disk, but was still connected with the limb by the black drop, or he might wait till the latter had disappeared, and the planet become wholly separated from the limb. The first of these was called apparent contact, the latter true contact, it being supposed that the latter marked the true time at which the actual contact took place. Again, when, at the end of the transit, the planet was about to pass off the sun, and was approaching the edge of his disk, the moment at which the black drop threw itself across the narrow space between the edge of the planet and that of the sun was considered to be the time of true contact; while the time at which the two limbs, could they have been traced all the way across the black drop, would have been tangent to each other marked apparent contact. Now, the ground taken by Mr. Stone was that certain observations which all previous investigators had interpreted as observations of true contact were really observations of apparent contact. The observations thus altered were those of the Abbé Chappe in San Jose, California, and those of Captain Cooke and his coadjutors in Otaheite. Those of Cooke's observations, which Encke and others had taken to refer to apparent contact, he rejected entirely, while he changed their true contacts into apparent ones. By these alterations he not only brought out a value of the sun's parallax sufficiently accordant with the modern determinations, but he brought all the observations into agreement with each other, thus, as he supposed, vindicating their accuracy.

If we wished to show the careful criticism to which every scientific result is now supposed to be subjected before it is accepted to be a mere pretence, we could not adduce stronger evidence for the ground taken than the treatment of Mr. Stone's paper by the astronomical writers of England. The average reader would have supposed, from the magazine and other articles, that he had solved the great problem of the century. It was strongly hinted that Encke did not understand the

nature and cause of the black drop, and had therefore blundered in his treatment of the observations. "It has been reserved for the genius of Mr. Stone to unravel those intricate appearances which just one century ago perplexed his predecessor, Mr. Green, at Otaheite." Until the occurrence of the transit of 1874, Mr. Stone's views were received as a sort of scientific gospel, to dispute which was a piece of foreign heresy. And yet it needed only an intelligent examination of the descriptions of the observers, as cited by Mr. Stone himself, to show that his interpretations were entirely inconsistent with them. In the case of Chappe's observation of egress, he assumes that that observer missed seeing the formation of the black drop as the planet was about to reach the edge of the sun, and this in face of the facts that Chappe not only clearly makes it known that he was looking for the black drop, and describes the contact as suddenly formed (which description could apply only to the black drop), but also minutely describes the precautions he took to catch the first appearance of the contact. As if to leave no doubt on the point, it happened that a young officer named Pauly, who was alongside of him, observing with a smaller telescope, noted the contact and left the instrument a few seconds earlier than Chappe, which gave the latter the occasion to say that he saw very well that Pauly was too soon. The changes made in the observations of Cook and Green at Otaheite are equally inadmissible; for although the description of the observers is less explicit than in the case of Chappe, yet they are accompanied by drawings which leave no reasonable doubt that if any change is to be made in Encke's interpretation, it is in the direction the opposite of Mr. Stone's.

We have said that the black drop was shown to be due to the imperfections of telescope-vision, giving rise to irradiation; and it was clearly shown years before the late transit, that if the circumstances permitted of good observations of contact, that is, if the atmosphere was steady and the telescope good, and if the observer was practised in its use, then scarcely a trace of black drop was seen. This proposition did not militate against the validity of Mr. Stone's interpretations of the observations of the old transit; still, it seemed to be considered by this gentleman

and his friends that the honor of his work depended on giving the black drop a good character; and they maintained, in the face of all the facts, that that phenomenon should always be seen by every good observer. This view led to positive evil in the observations of the late transit by mystifying the observers, and leading them to devote their attention to looking for something which they would probably not see at all except in imagination. As a matter of fact, it was found that, except Mr. Stone himself, scarcely any able and practised observers saw the black drop.

The opinion now generally held respecting the cause of the error in the old determination of the distance of the sun is, that it is due simply to the uncertainties and difficulties of the observations. Various results can be obtained by changing the mode of treatment, but no legitimate treatment will give a result materially different from that of Encke. The questions which now most interest us are, how certain a result will be given by the observations of the late transit, and whether it will be worth while to send out expeditions to observe the transit of 1882. On the first very little light can be thrown until the observations are completely worked up, and those of different nations compared. No attempt should be made to foresee the result till it is actually reached, and this will require at least two years, and perhaps more. While there is no doubt that the results will be in every way far more reliable and accurate than those of 1769, there is little hope that they will entirely supersede those derived in other ways, and it may even be found that other methods than transits of Venus will be more accurate and less laborious.

Perhaps the most promising of these methods is that of the velocity of light. The time required by light in passing from the sun to the earth admits of being determined within its thousandth part, and it only requires a correspondingly accurate knowledge of its velocity to determine the distance of the sun with an accuracy exceeding that obtained in any other way. The apparatus will be expensive, and the experiments laborious, but the results attainable will amply compensate both the labor and the expense.

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